# FRIB transition to user operations, power ramp up, and upgrade perspectives

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On Behalf of FRIB Accelerator Team & Collaboration

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Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

# Outline

- Introduction
- Complexity and lessons learned
- Down time, performance and reliability, power ramp up
- Improvements and investments
- FRIB400: energy upgrade
- Summary

# Introduction

# FRIB Technical Construction 2014 – 2022

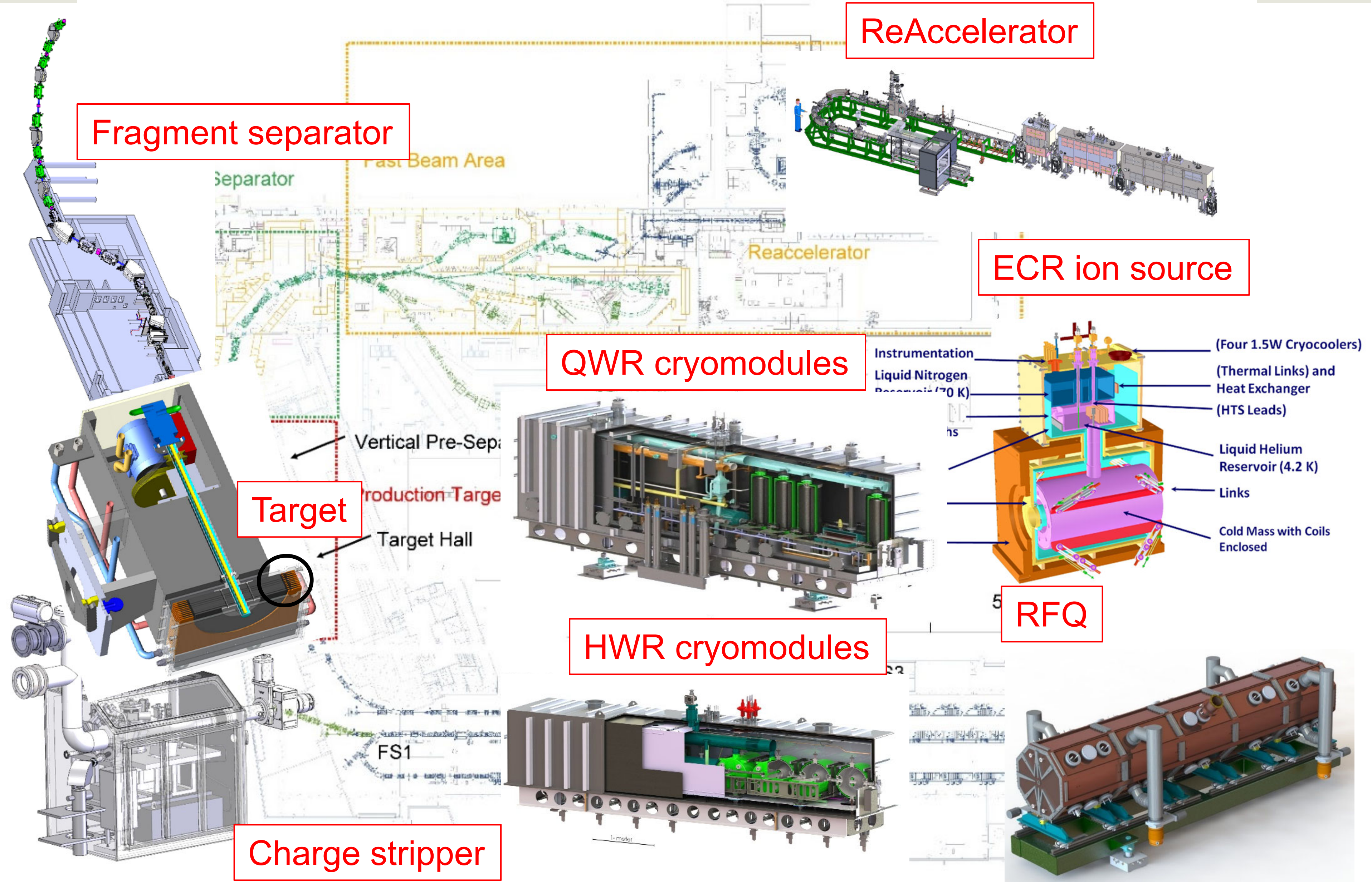
## World’s Highest Energy Heavy Ion Linac / CW Hadron Linac

**FRIB driver linac in accelerator tunnel**

| Milestones | Date |
|---|---|
| DOE and MSU cooperative agreement | Jun 2009 |
| CD-1: preferred alternatives decided | Sep 2010 |
| CD-2/CD-3a: performance baseline, start of civil construction & long lead procurement | Aug 2013 |
| CD-3b: start of technical construction | Aug 2014 |
| FRIB linac construction completion | May 2021 |
| Project technical construction completion | Jan 2022 |
| CD-4: project completion | Apr 2022 |
| Start of PAC1 user experiments at 1 kW beam power | May 2022 |
| User experiments at 5 kW primary beam power | Feb 2023 |

- FRIB linac includes the front end and 46 superconducting RF cryomodules
  - ECR ion sources, RFQ
  - 324 SRF cavities in 46 cryomodules with velocity $\beta$ from 0.041 to 0.53
  - 208 cold magnets, 350 warm magnets
- Liquid helium for 2 K, 4 K operations
- Liquid lithium charge stripping and rotating target for isotope production

# Accelerator Complex with Separation of Isotopes In-flight: Fast, Stopped, and Reaccelerated Beams



ReAccelerator

Fragment separator

ECR ion source

QWR cryomodules

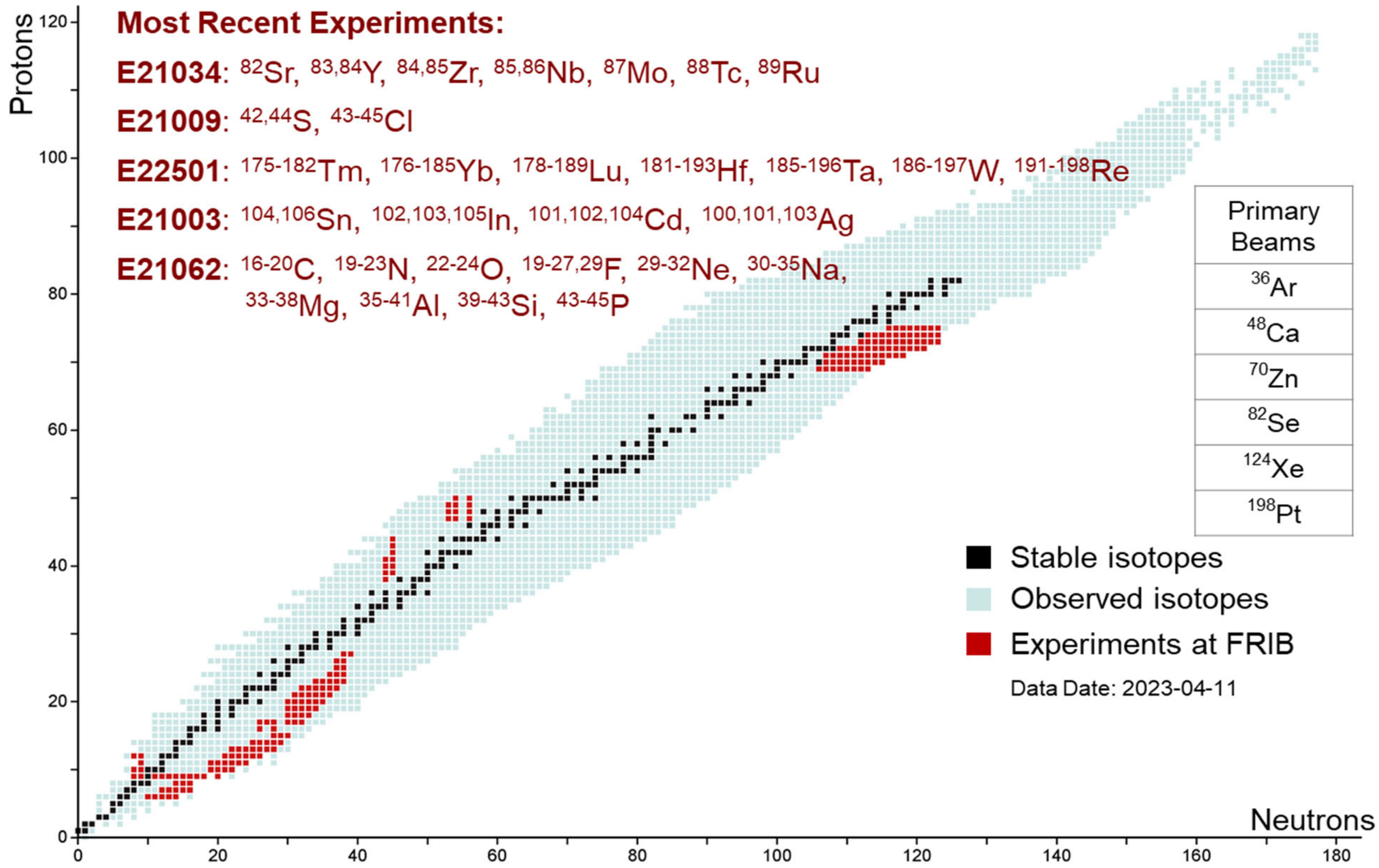
Target

RFQ

HWR cryomodules

Charge stripper

# More than 200 Rare Isotope Beams Delivered to Nine FRIB User Experiments for Year 1



**Most Recent Experiments:**

**E21034**: $^{82}$Sr, $^{83,84}$Y, $^{84,85}$Zr, $^{85,86}$Nb, $^{87}$Mo, $^{88}$Tc, $^{89}$Ru

**E21009**: $^{42,44}$S, $^{43-45}$Cl

**E22501**: $^{175-182}$Tm, $^{176-185}$Yb, $^{178-189}$Lu, $^{181-193}$Hf, $^{185-196}$Ta, $^{186-197}$W, $^{191-198}$Re

**E21003**: $^{104,106}$Sn, $^{102,103,105}$In, $^{101,102,104}$Cd, $^{100,101,103}$Ag

**E21062**: $^{16-20}$C, $^{19-23}$N, $^{22-24}$O, $^{19-27,29}$F, $^{29-32}$Ne, $^{30-35}$Na, $^{33-38}$Mg, $^{35-41}$Al, $^{39-43}$Si, $^{43-45}$P

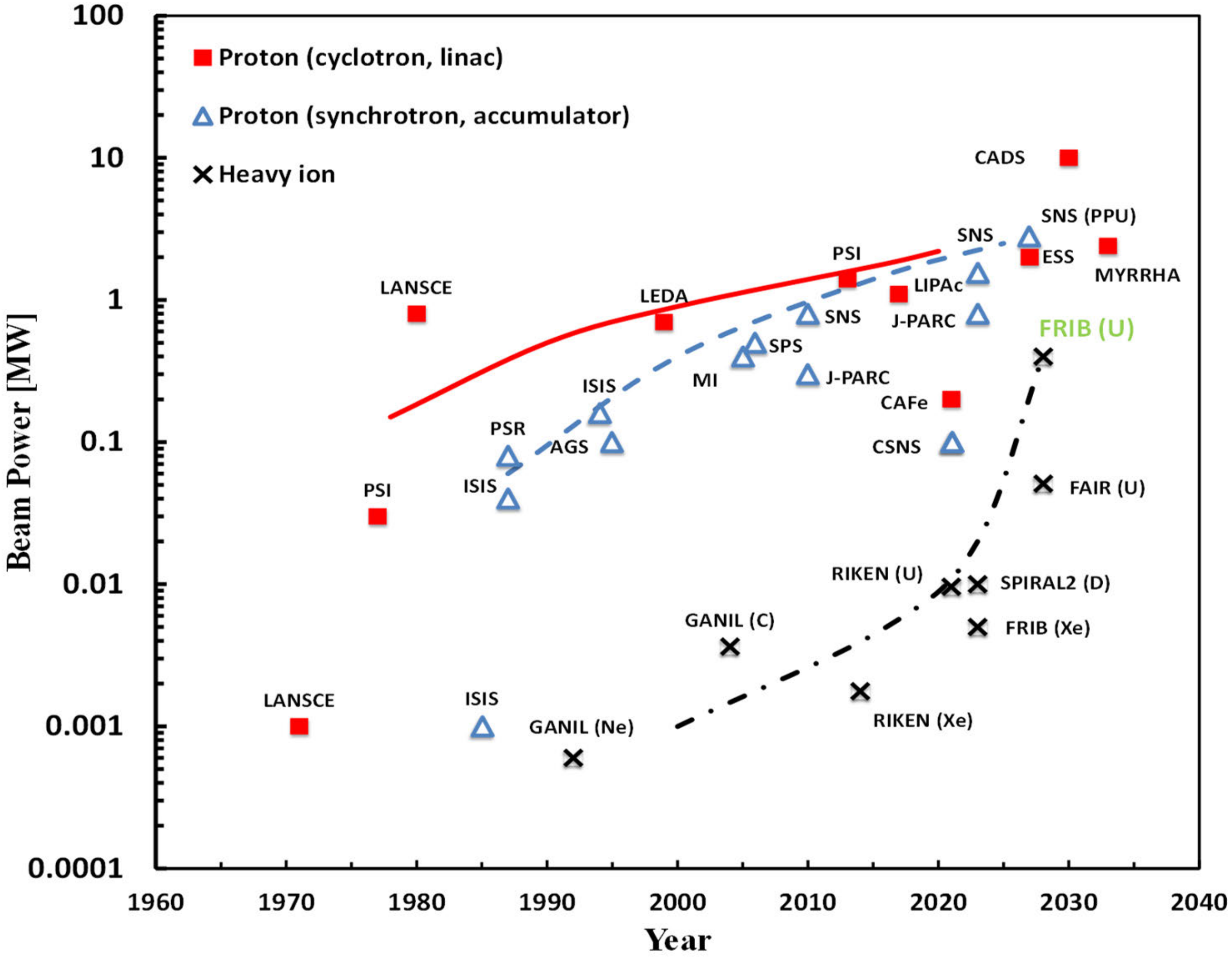
| Primary Beams |
|---|
| $^{36}$Ar |
| $^{48}$Ca |
| $^{70}$Zn |
| $^{82}$Se |
| $^{124}$Xe |
| $^{198}$Pt |

Data Date: 2023-04-11

# Complexity and lessons learned

# Evolution of Proton and Heavy Ion Beam Power

- Comparing with proton-based facilities, lower-energy, heavy-ion based facilities face challenges including high dissipation-power density and high radiation damages



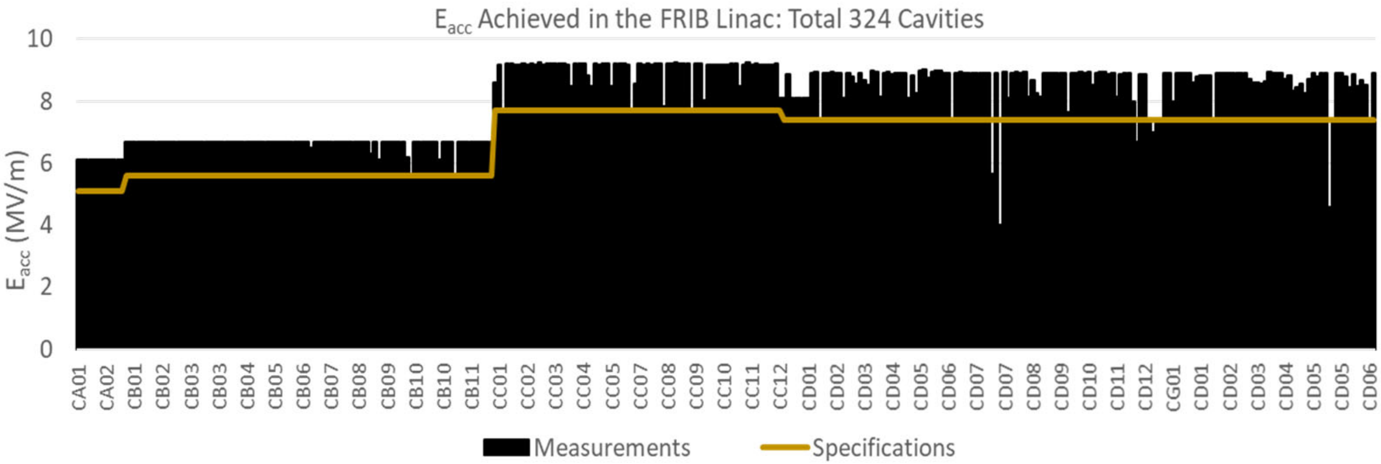
- FRIB started user operations at 1 kW
- Currently operating at 5 kW for year-1
- Aim at reaching 400 kW around 2028

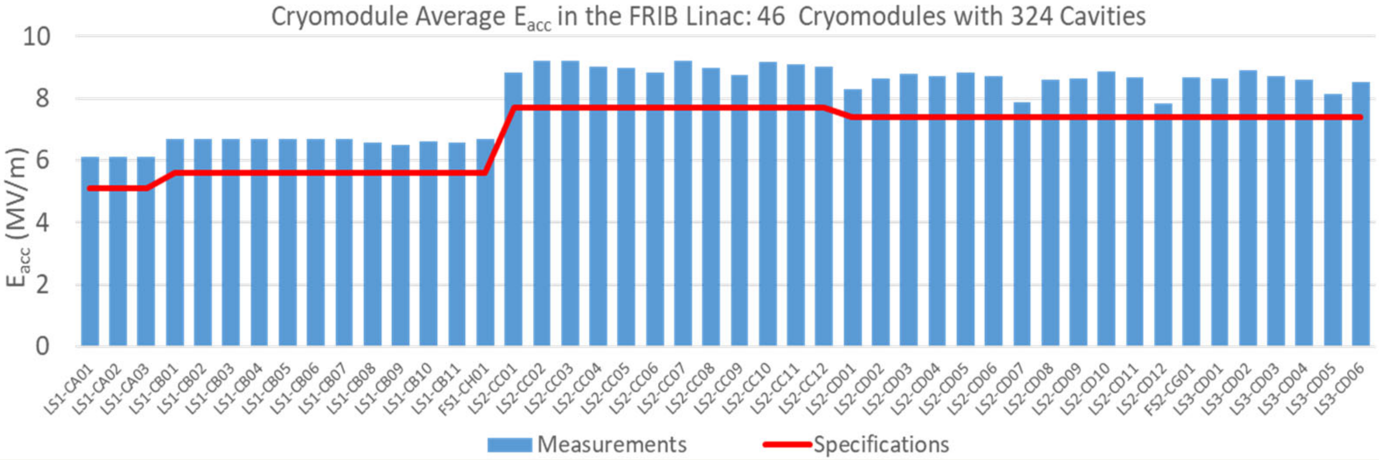
# FRIB Facility Challenges and Complexity

- Large-scale low-β superconducting linac
- High-power beam-intercepting devices
  - Charge stripping and charge collection devices
  - Target and beam dump devices
- Multiple charge-state acceleration
- Advanced Rare Isotope Separator complexity
- Legacy system interfacing and integration
- Multi-layered machine protection

# Large-scale Low-β Superconducting Linac

- Integrated design of cryogenics, cryo-distribution, and cryomodules

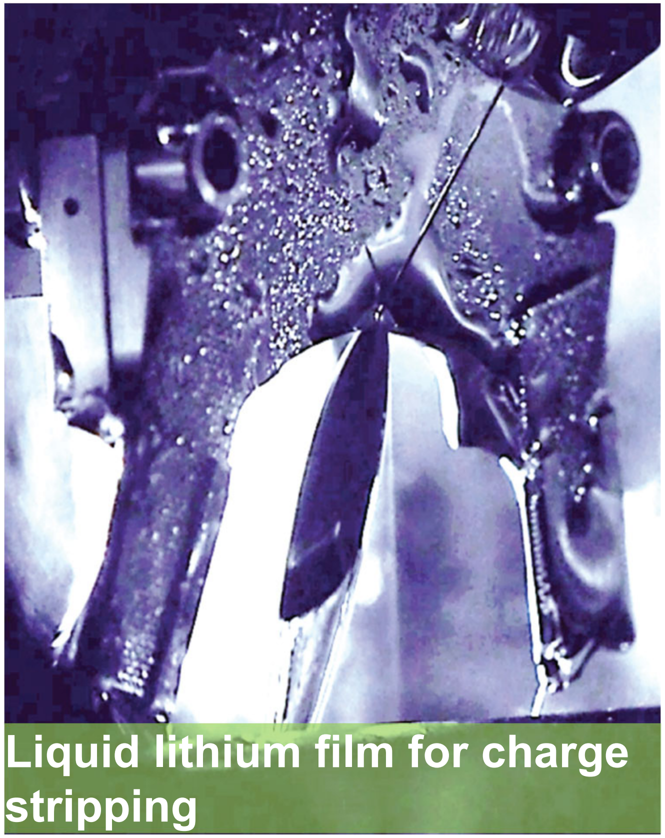

$E_{acc}$ Achieved in the FRIB Linac: Total 324 Cavities


Cryomodule Average $E_{acc}$ in the FRIB Linac: 46 Cryomodules with 324 Cavities

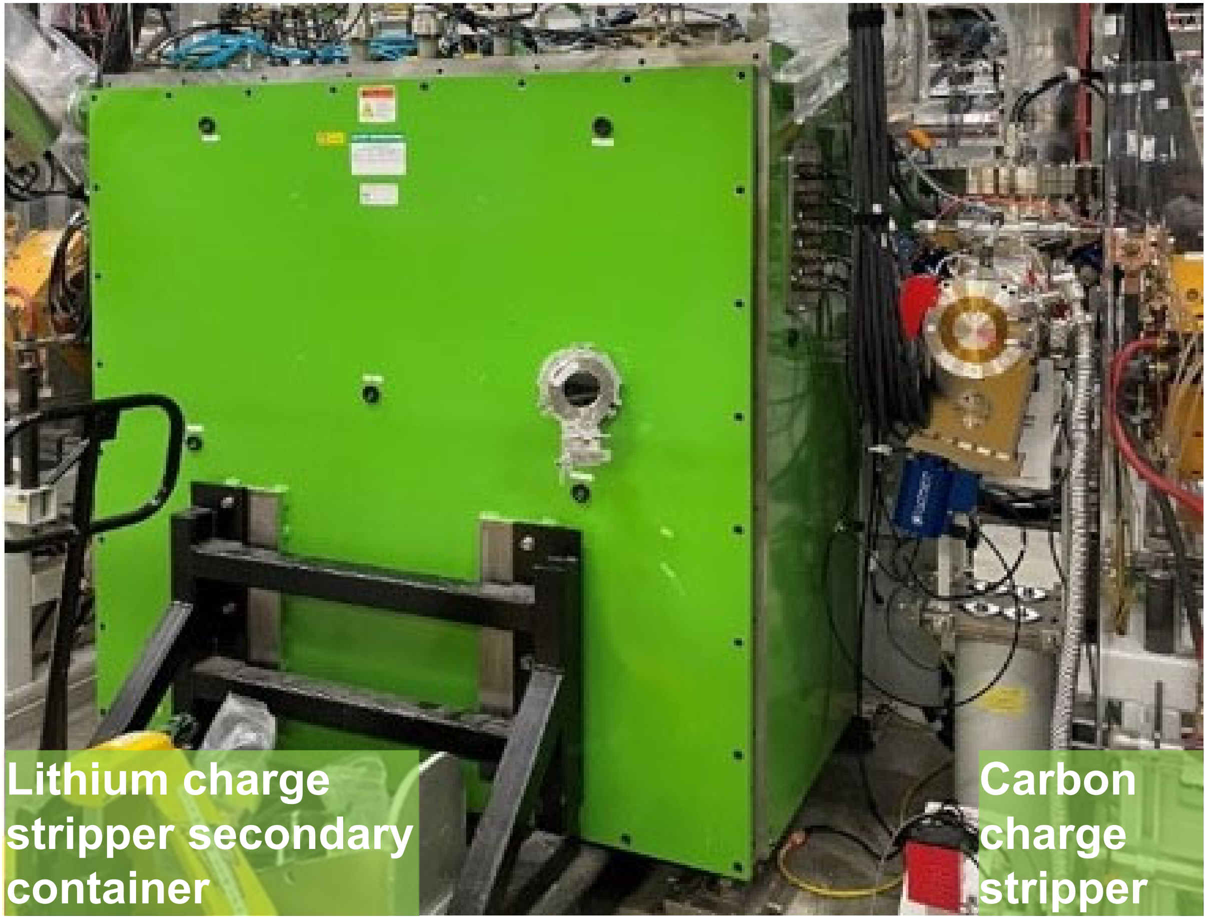
- All resonators can operate at either 2 K or 4.5 K
- In operations, HWR runs at 2 K, while QWR and SC magnets run at 4.5 K
- All performing on specifications
- No obvious signs of beam-induced degradations

# High-power Charge-stripping Devices

- Operating with charge strippers of either liquid-lithium film (for high-power operation) or rotating carbon foil (for light ions)



**Liquid lithium film for charge stripping**



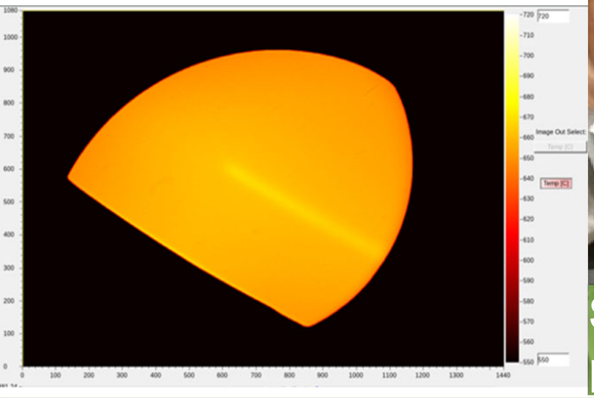
**Lithium charge stripper secondary container**

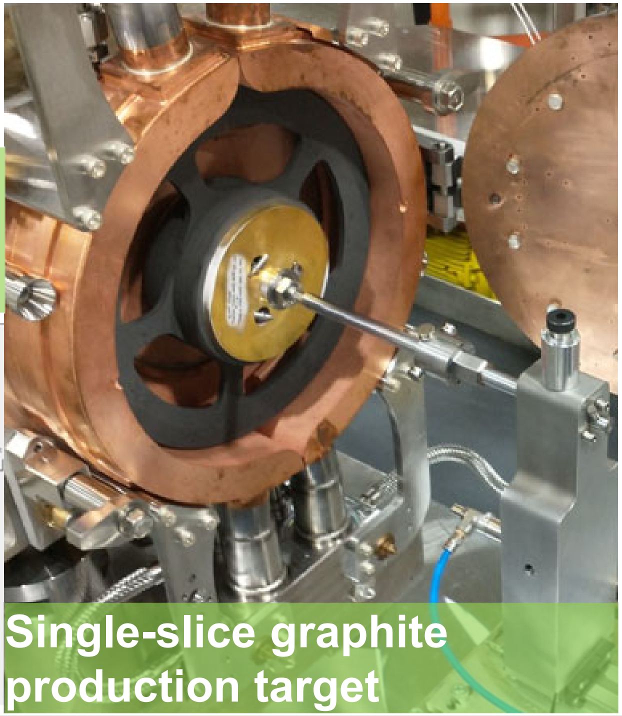
**Carbon charge stripper**

# High-power Targetry Devices

- Rotating, single-slice graphite target for rare isotope production
  - Absorbs ~ 25% beam power; accommodate small (~ Ø 1 mm) beam size
- Static beam dump with shallow beam incident angle
  - Absorbs ~ 75% beam power; consideration of radio-activation in water and surroundings

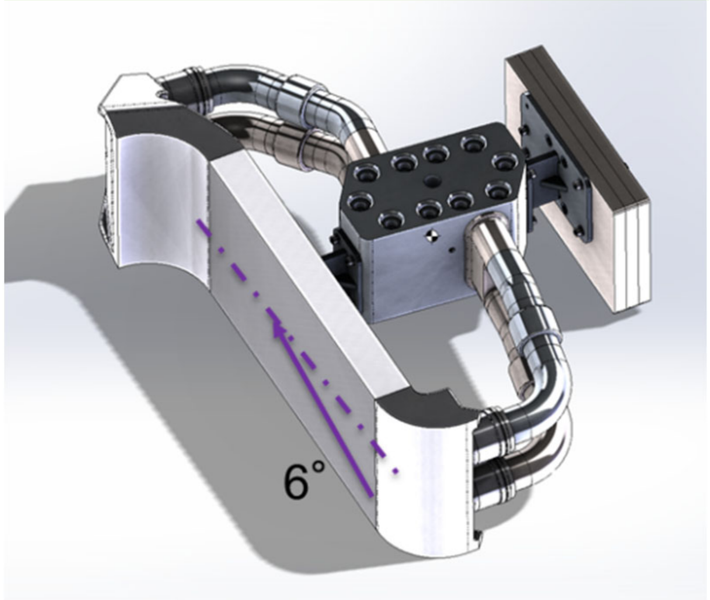
**5 kW, 240 MeV/u $^{64}$Zn beam on the target rotating at 500 revolutions per minute**





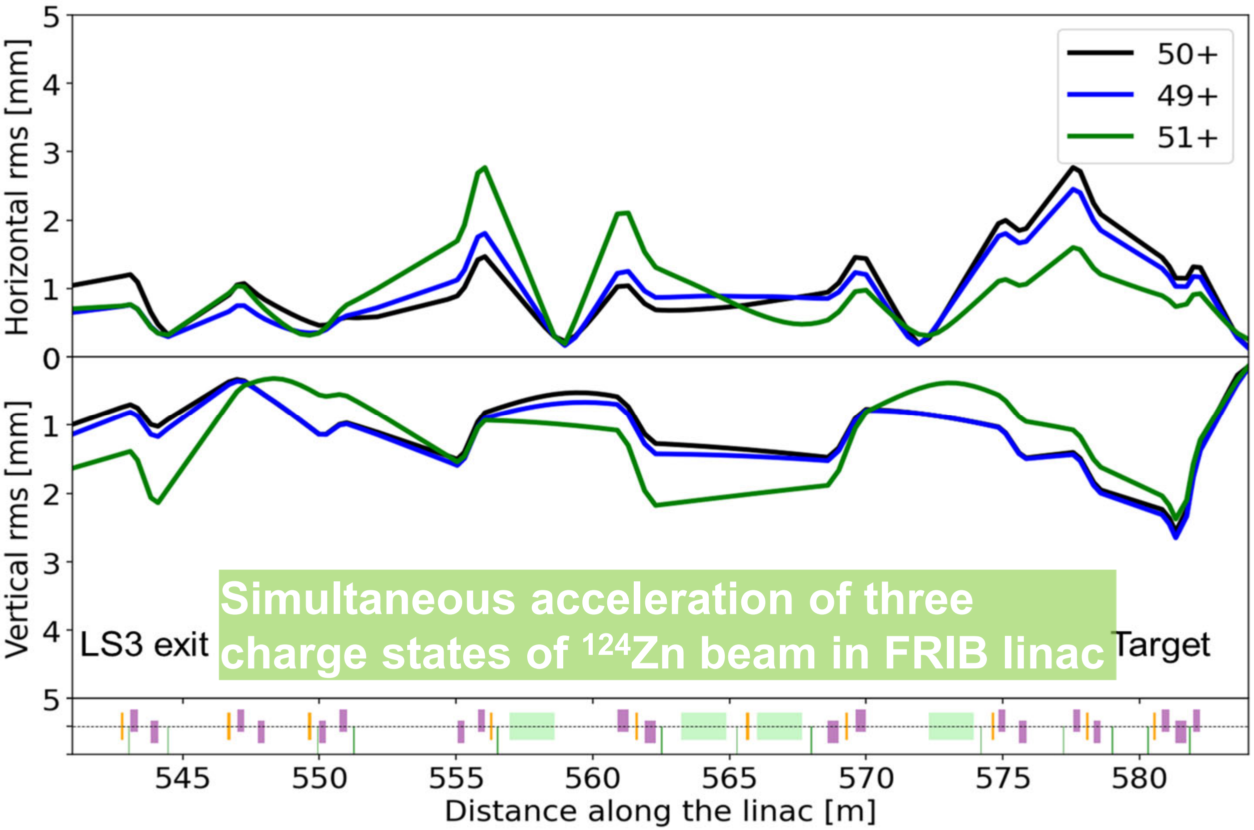
**Single-slice graphite production target**

**Static beam dump with 6º beam incident angle**



# Multiple Charge-state Acceleration

- Routinely accelerating up to three charge state simultaneously to enhance beam intensity and reduce controlled beam loss downstream of charge stripper

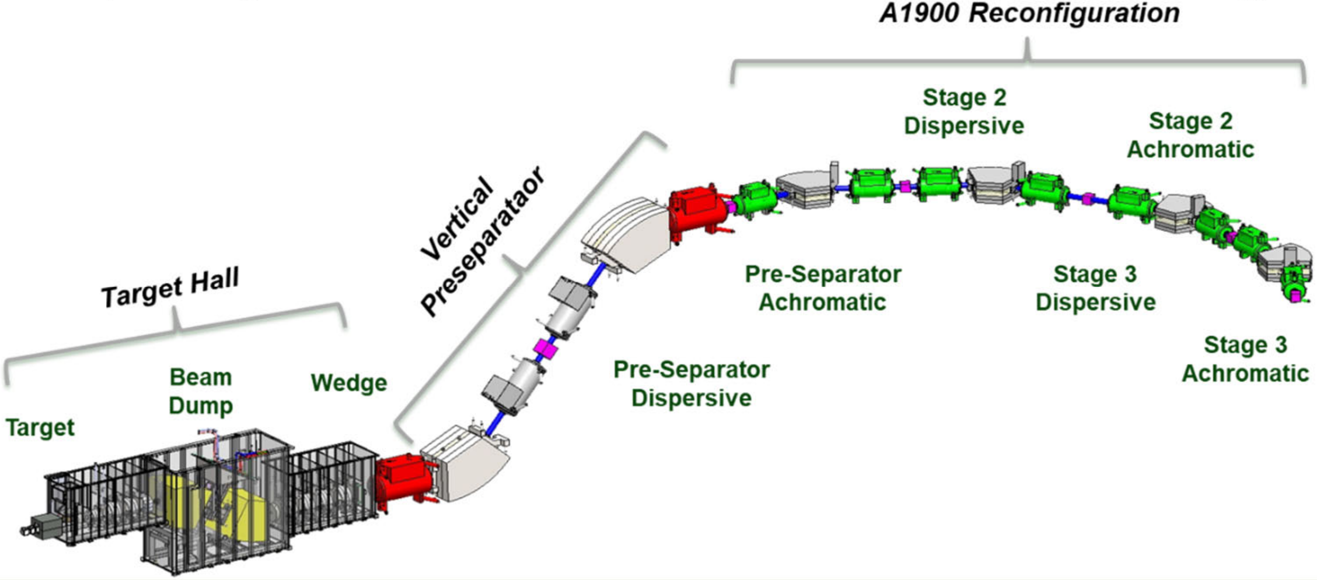


Simultaneous acceleration of three charge states of $^{124}$Zn beam in FRIB linac

- Beams of multi charge states tuned to overlap at specified locations
  - Target (present)
  - Charge stripper (future)
- Will extend work to linac segment 1 (upstream of charge stripper)

# Advanced Rare Isotope Separator complexity

- Collects ~ 100% fragments produced at the target; select individual isotopes for delivery to desired experimental station
  - Three stages fragment separation
    - In-flight rigidity selection and selective energy loss in profiled degraders
  - Combination of vertical and horizontal separation
    - Momentum compression in the vertical plane
    - Preserves good phase space for gas stopping in the horizontal plane
  - Optically corrected to 3rd order and operate over rigidity range of 1 to 8 T·m

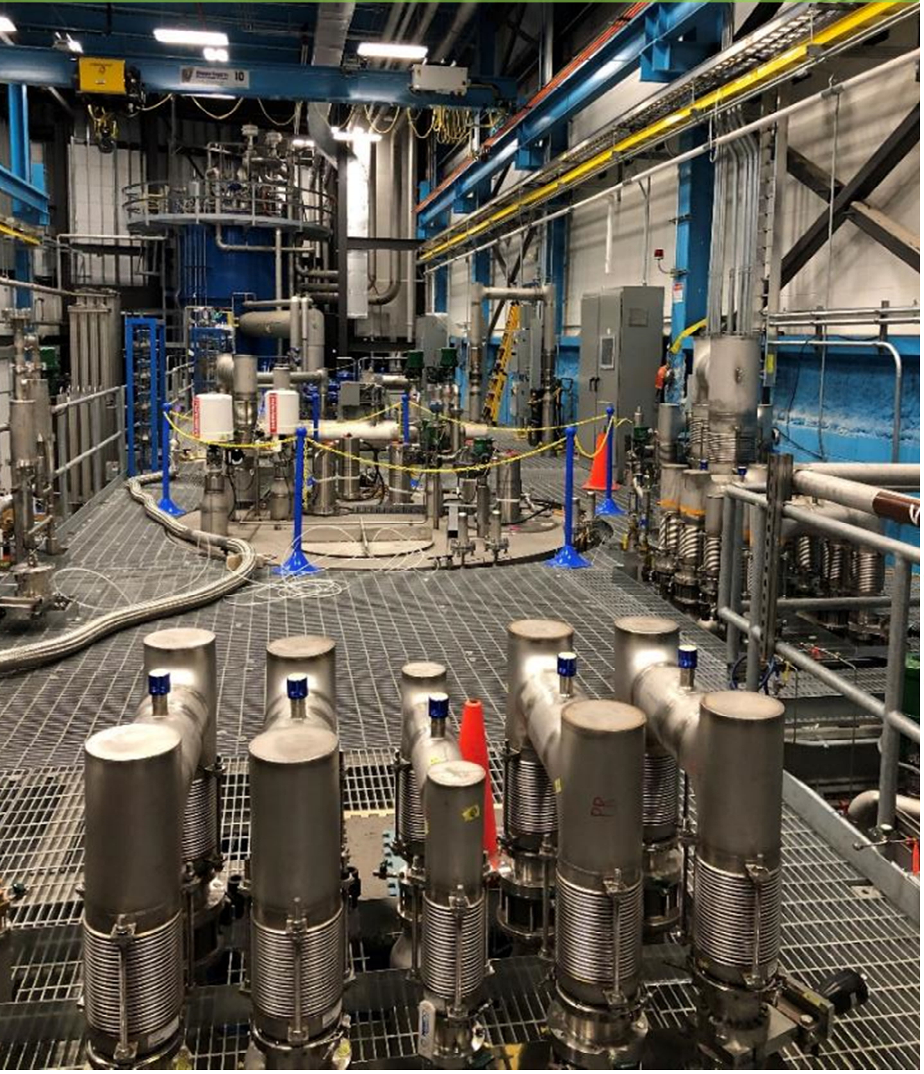


- Issues:
  - Newly constructed VPS meets legacy A1900 reconfigured
    - Aperture limited
    - Magnets not compensated
    - Lack of diagnostics and correctors

# Legacy System Interfacing and Integration

## Legacy Cryogenic System Demands Renovation & Integration

**FRIB's state-of-the-art, highest efficiency helium refrigeration system supporting both 2 K & 4.5 K loads**

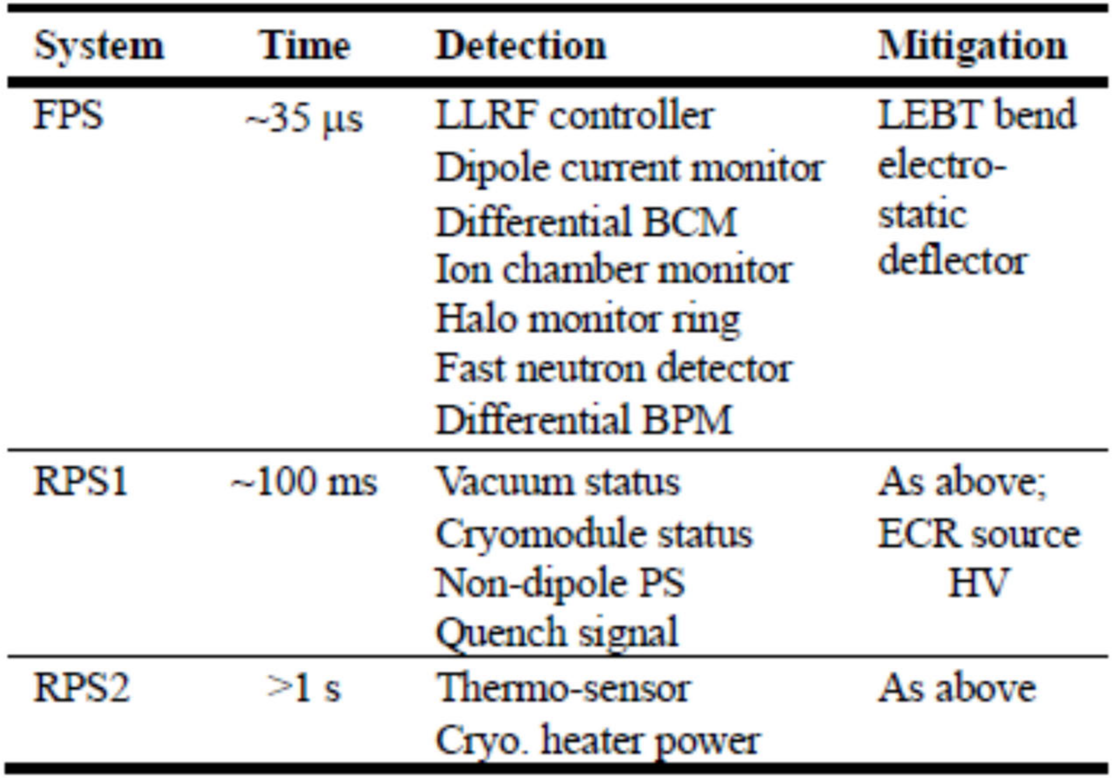


- NSCL "green cold box" is < 30% efficient and less reliable than FRIB central helium liquefier (cryoplant)
- FRIB experimental area cryogenics are designed to a higher pressure rating to recover helium from magnet quenches and for increase availability
- FRIB 35 – 55 K shield allows HTS (high temperature superconductor) application for magnets

**Legacy NSCL "green cold box" supporting experimental cryogenic distribution / devices**

# Multi-layered Machine Protection

- High power, low-energy ions beams: short stopping range and high power density
- Must mitigate both acute & chronicle beam loss (by beam inhibition)



| System | Time | Detection | Mitigation |
|---|---|---|---|
| FPS | ~35 μs | LLRF controller<br>Dipole current monitor<br>Differential BCM<br>Ion chamber monitor<br>Halo monitor ring<br>Fast neutron detector<br>Differential BPM | LEBT bend electrostatic deflector |
| RPS1 | ~100 ms | Vacuum status<br>Cryomodule status<br>Non-dipole PS<br>Quench signal | As above; ECR source HV |
| RPS2 | >1 s | Thermo-sensor<br>Cryo. heater power | As above |

- Used extensively in driver linac
- Need to extend use in high power targetry systems

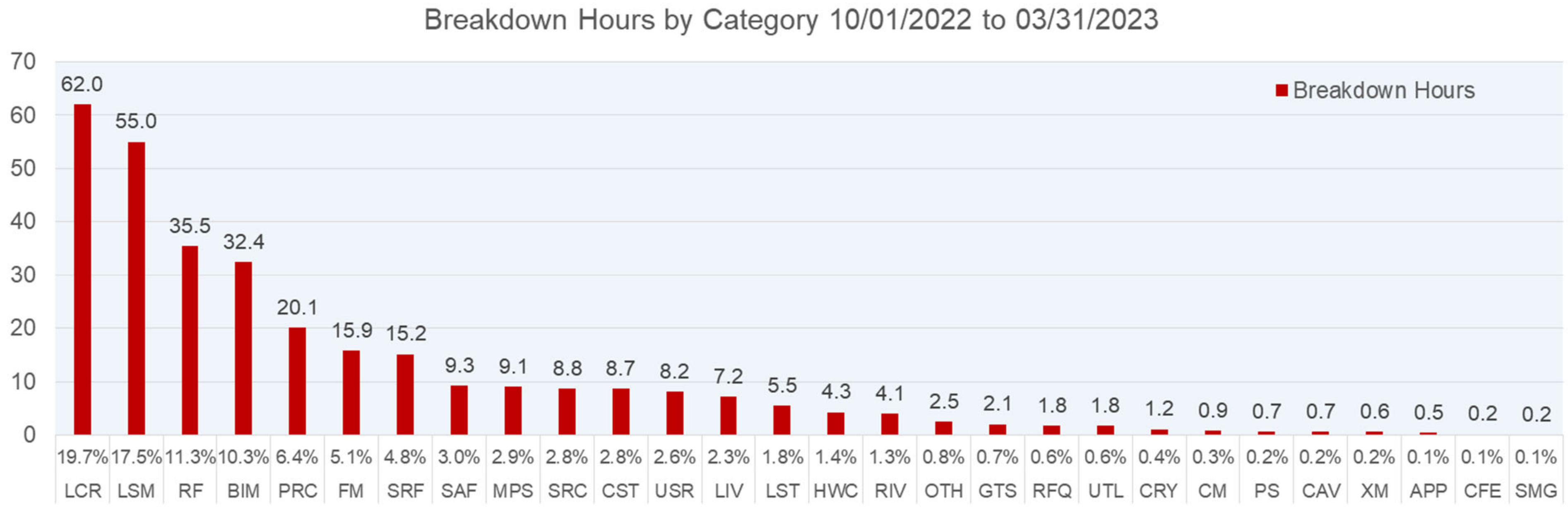
# Lessons Learned during FRIB Construction

- Recruit worldwide and retains key subject matter experts (**own the best people**)
- Develop and mature key technologies in time to support the project schedule (**own the technology**)
- Align interests for infrastructure investment to support key construction steps and future research (**align interests, invest in infrastructure**)
- Closely collaborate with US national labs and worldwide partners for knowledge transfer and project support; rigorously manage collaboration (**collaborate without losing control**)
- Strategically facilitate phased commissioning to stagger work force, validate design principles, feed back on improvements, and meet schedule (**phase the scope for optimization**)
- Conduct rigorous external reviews, inviting the best experts to critique the work (**review rigorously**)
- Engage with industrial providers via exchange visits, weekly meetings, and extended stays (**intimately engage vendors**)
- The original "turn-key" approach to procure the large-scale cryogenic helium system from industry exposed the project to serious risks in budget and scope (**avoid "turn-key" on large-scale cryogenics**)
- Early shortcuts taken in SRF/QWR sub-component validation was costly (**avoid shortcuts**)
- Shared vacuum vessels in the target area complicate maintenance (**consider maintenance**)
- Lack of diagnostics and correctors in the 3D geometric layout complicates fragment separation (**ensure adequate diagnostics and adjustments**)
- Conduct systematic R&D for novel technology, e.g. bottom-up cryomodule (**systematic R&D**);
- Thorough testing is needed for all major technical equipment, e.g. SRF sub-components, cryomodules, superconducting magnets (**test thoroughly**)
- Pro-actively facilitate critical system validation, e.g. for liquid Li stripper (**facilitate critical validation**)

# Down time, performance and reliability, power ramp up

# Delivered 5250 Hours Year 1; 92% Availability

## 1528 Hours for Scientific users; 2724 Hours for Beam Development, Studies and Tuning; 998 Hours for FSEE Beamline

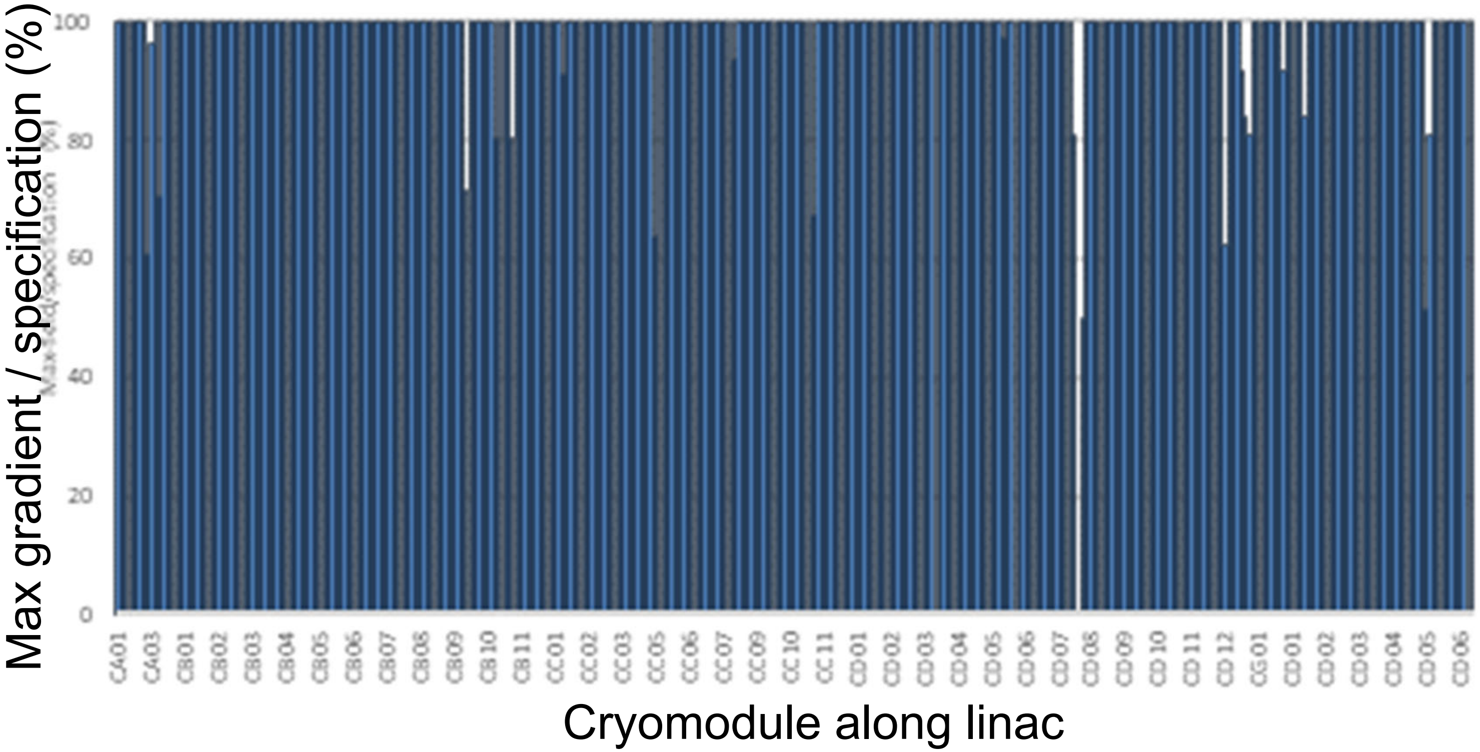


Breakdown Hours by Category 10/01/2022 to 03/31/2023

| | | | | | |
|---|---|---|---|---|---|
| LCR | Legacy Cryogenics | CST | Carbon stripper | CRY | Cryogenics |
| LSM | Legacy Superconducting Magnets | USR | User related issue | CM | Cryomodules |
| RF | Radio frequency systems | LIV | Linac beamline vacuum | PS | Power Supplies |
| BIM | Beam instrumentation | LST | Lithium Stripper | CAV | Normal conducting cavities |
| PRC | Procedural Violation/Investigation | HWC | Hardware Controls | XM | X-ray monitors |
| FM | Force Majeure | RIV | Rare isotope vacuum | APP | Control applications |
| SRF | Superconducting RF (cavity trips) | OTH | Other | CFE | Conventional facility electricity |
| SAF | Safety systems, incl. monitors | GTS | Global timing system | SMG | Superconducting Magnets |
| MPS | Machine protection and global systems | RFQ | RFQ | | |
| SRC | Ion sources | UTL | Utilities | | |

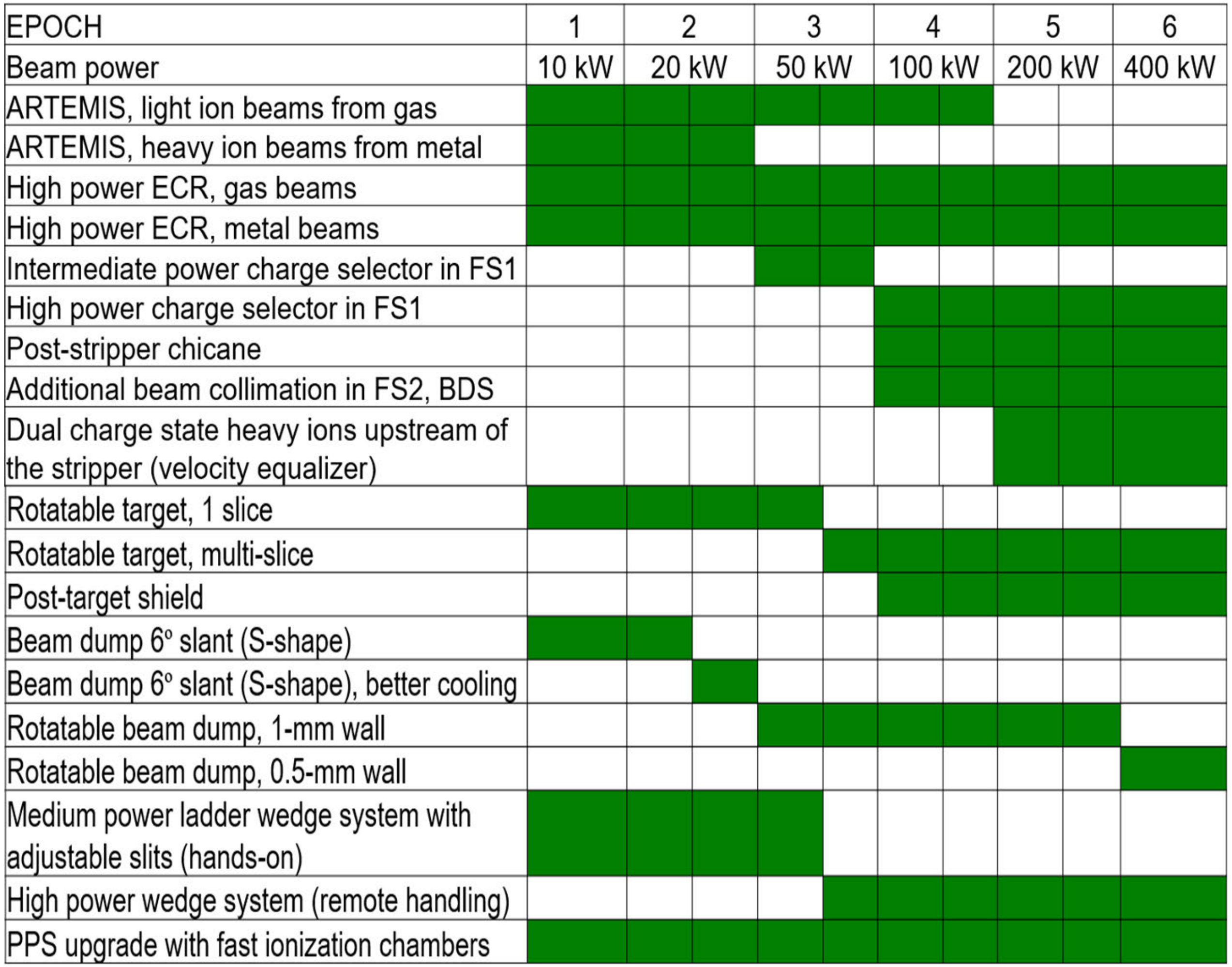
# SRF Performances in Operations

- Four out of 324 cavities currently not being used in operations until the next maintenance period
  - Replacement of failed power coupler; cold cathode gauge; pneumatic tuner gas line cleaning; gas line operating pressure



- Plan to swap 1 – 2 cryomodules per year for optimal performance
- Developing plasma processing for in-situ cleaning

# A Safe Power Ramp Up with Phased Deployment



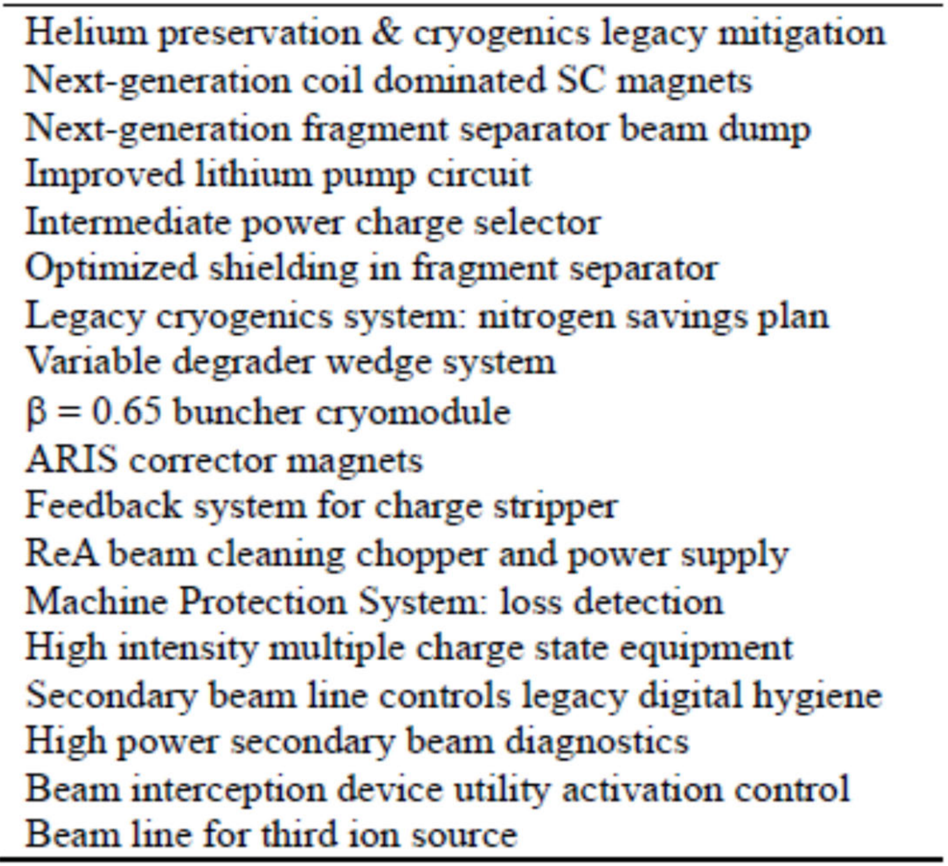
| EPOCH | 1 | 2 | | 3 | | 4 | | 5 | | 6 |
|---|---|---|---|---|---|---|---|---|---|---|
| Beam power | 10 kW | 20 kW | | 50 kW | | 100 kW | | 200 kW | | 400 kW |
| ARTEMIS, light ion beams from gas | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | |
| ARTEMIS, heavy ion beams from metal | 🟩 | 🟩 | 🟩 | | | | | | | |
| High power ECR, gas beams | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| High power ECR, metal beams | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Intermediate power charge selector in FS1 | | | | 🟩 | 🟩 | | | | | |
| High power charge selector in FS1 | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Post-stripper chicane | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Additional beam collimation in FS2, BDS | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Dual charge state heavy ions upstream of the stripper (velocity equalizer) | | | | | | | | 🟩 | 🟩 | 🟩 |
| Rotatable target, 1 slice | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | |
| Rotatable target, multi-slice | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Post-target shield | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Beam dump 6° slant (S-shape) | 🟩 | 🟩 | | | | | | | | |
| Beam dump 6° slant (S-shape), better cooling | | | 🟩 | | | | | | | |
| Rotatable beam dump, 1-mm wall | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |
| Rotatable beam dump, 0.5-mm wall | | | | | | | | | | 🟩 |
| Medium power ladder wedge system with adjustable slits (hands-on) | 🟩 | 🟩 | 🟩 | 🟩 | | | | | | |
| High power wedge system (remote handling) | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| PPS upgrade with fast ionization chambers | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

- Planned power ramp up in 6 years
  - Progressively increase average beam current
- Phased deployment of several systems
  - Beam intercepting systems
  - Personnel protection system
  - Radio-activation control

# Improvements and investments

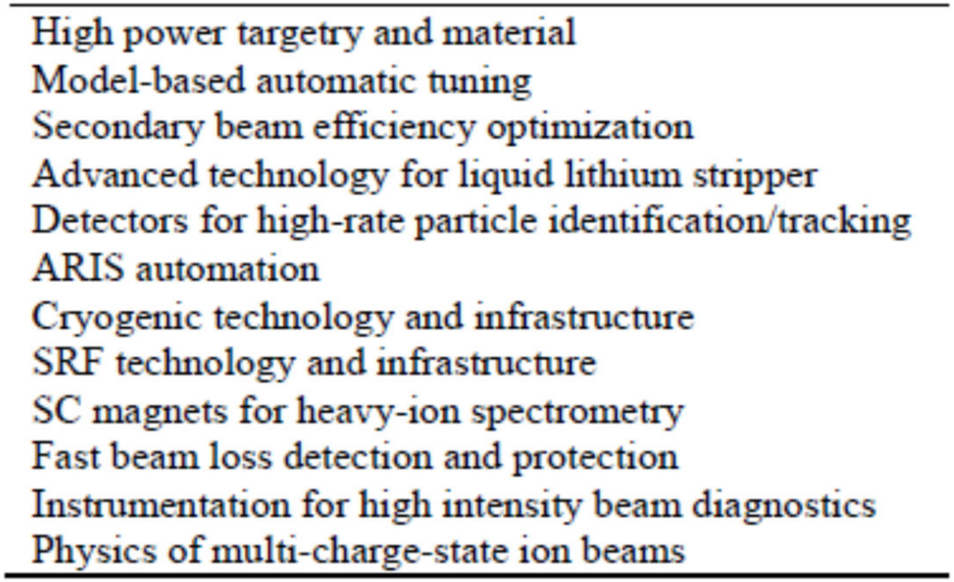
# Accelerator Improvements and R&D Are Essential for Availability and Power Ramp Up

- Examples of accelerator improvement projects and capital equipment investments



Helium preservation & cryogenics legacy mitigation
Next-generation coil dominated SC magnets
Next-generation fragment separator beam dump
Improved lithium pump circuit
Intermediate power charge selector
Optimized shielding in fragment separator
Legacy cryogenics system: nitrogen savings plan
Variable degrader wedge system
$\beta = 0.65$ buncher cryomodule
ARIS corrector magnets
Feedback system for charge stripper
ReA beam cleaning chopper and power supply
Machine Protection System: loss detection
High intensity multiple charge state equipment
Secondary beam line controls legacy digital hygiene
High power secondary beam diagnostics
Beam interception device utility activation control
Beam line for third ion source

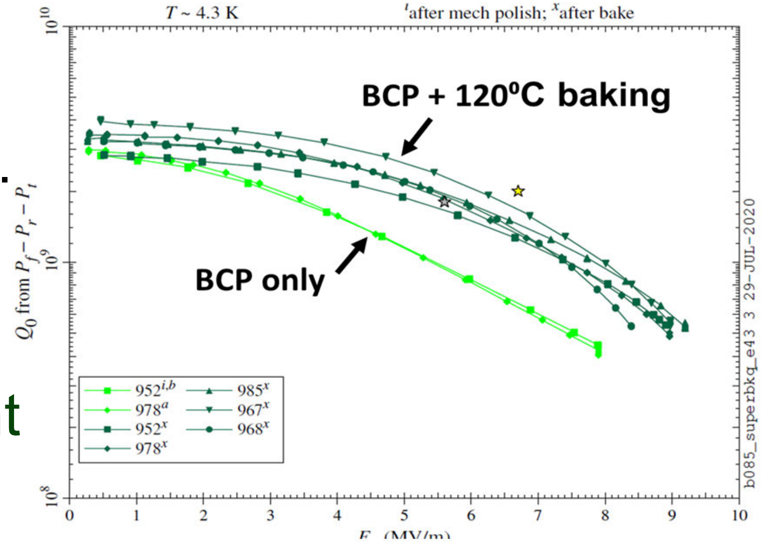
- Examples of planned accelerator R&D

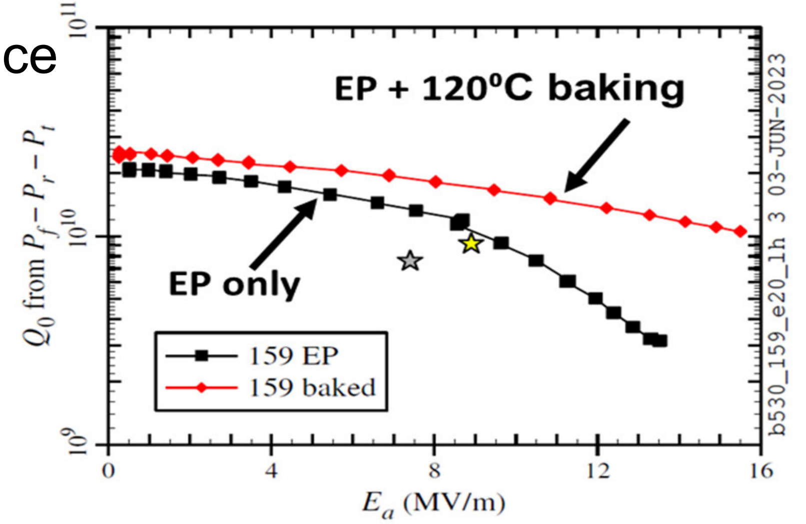


High power targetry and material
Model-based automatic tuning
Secondary beam efficiency optimization
Advanced technology for liquid lithium stripper
Detectors for high-rate particle identification/tracking
ARIS automation
Cryogenic technology and infrastructure
SRF technology and infrastructure
SC magnets for heavy-ion spectrometry
Fast beam loss detection and protection
Instrumentation for high intensity beam diagnostics
Physics of multi-charge-state ion beams

# SRF Improvement and Development Example

- Plasma processing
  - W. Hartung *et al.*, “Investigation of plasma processing for coaxial resonators,” THIXA01.
- Optimization for 4 K operation
  - Improved quality factor with 120ºC baking
- HWR High-field performance improvement
  - K. Saito, “Development of transformative cavity processing: superiority of electropolishing on high gradient performance over buffered chemical polishing at low frequency (322 MHz),” MOPMB026.
- In-situ swapping of FPC RF windows
  - S. Kim, “FRIB commissioning and first operation,” *TTC’22*, Aomori, Japan, 2022.



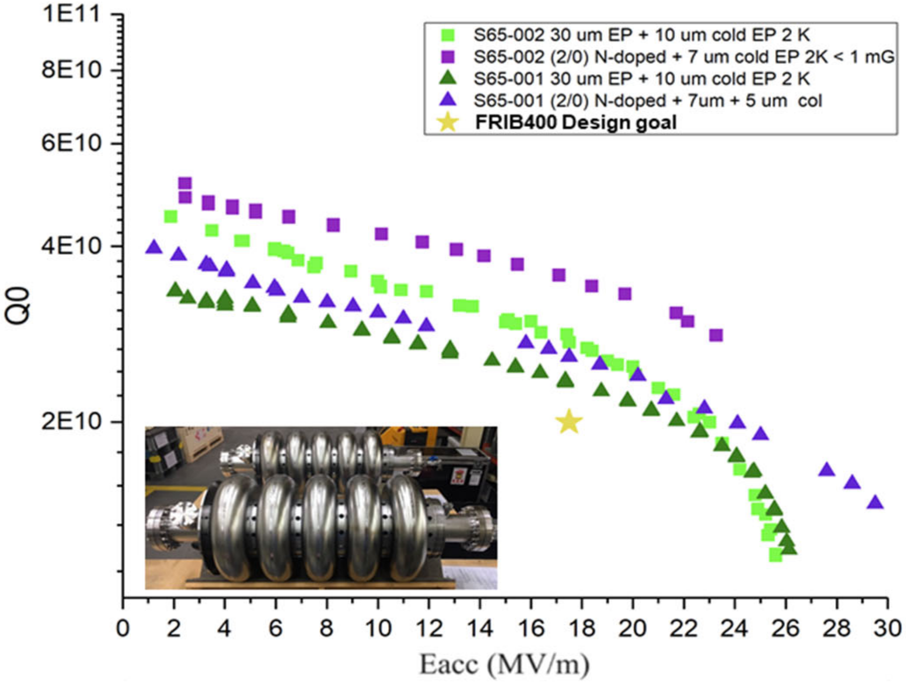


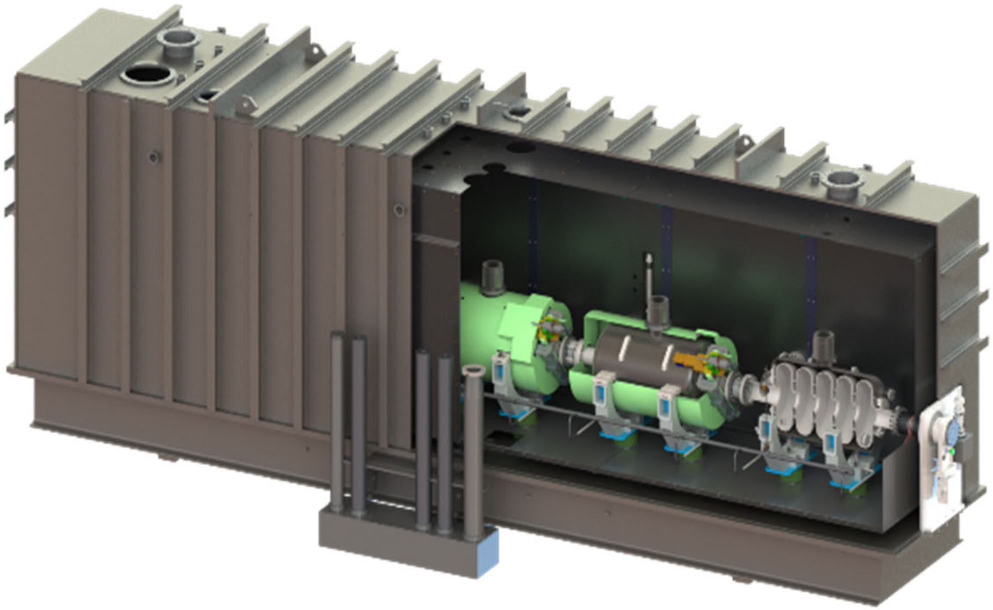
**Facility for Rare Isotope Beams**
U.S. Department of Energy Office of Science
Michigan State University

# FRIB400: energy upgrade

# FRIB400: Extend Scientific Reach and Discovery Potential

- Doubles linac beam energy (to 400 MeV/u for uranium) by adding 11 cryomodules, each containing 5 (β = 0.65) cavities at 644 MHz
  - Filling reserved slots in FRIB tunnel
  - Expanding cryo-distribution
- R&D and design in progress





# Summary

# Collaboration with National Laboratories and International Partners: Key to Success

- ANL
  - Liquid lithium charge stripper
  - Beam dynamics verification ; β=0.29 HWR processing and testing ; SRF tuner validation ; beam dump ; SRF components development
  - RF couplers for multi-gap buncher
  - SOLARIS
- BNL
  - Plasma window & charge stripper, physics modeling, magnets
- FNAL
  - Diagnostics, SRF processing
- JLab
  - Cryoplant; cryodistribution design & prototyping
  - Cavity hydrogen degassing; e-traveler
  - HWR processing & certification
  - QWR and HWR cryomodule design and engineering support for production
- LANL
  - Proton ion source
- LBNL
  - ECR coldmass; beam dynamics
- MIT
  - CRIS
- ORNL
  - Remote handling, diagnostics; large-vessel vacuum, cryoplant controls
  - FDSi
- SLAC
  - Cryogenics, SRF multipacting, physics modeling
- RIKEN
  - Helium gas charge stripper
- TRIUMF
  - Beam dynamics design, physics modeling SRF, QWR etching
- INFN
  - SRF technology
- KEK
  - SRF technology, SC solenoid prototyping
- IMP
  - Magnets
- Budker Institute, INR Institute
  - Diagnostics
- Tsinghua Univ. & CAS
  - RFQ
- ESS
  - Accelerator physics
- DTRA
  - RFQ power supply
- CSNSM-JaNNUS
  - Nuclear recoil damage to materials
- RaDIATE
  - Nuclear recoil damage to materials
- GANIL
  - Rare isotope physics, target development
- GSI
  - Rare isotope physics, fragment separators
- U Notre Dame
  - Recoil implantation testing of materials

# Summary

- FRIB has been operating for a year, delivering beams for both scientific and industrial experiments with the desired reliability and availability
- The primary beam power has been steadily raised from 1 to 5 kW. In subsequent years, the beam power will be progressively increased as operational experience is accumulated, working toward 400 kW
- Accelerator improvement projects, capital equipment investments, and R&D projects are in progress to renovating legacy systems and maintain high availability during the beam power ramp-up
- Work is proceeding in preparation for future upgrades, including a doubling of the primary beam energy to 400 MeV/u to enhance the scientific reach of the facility

# Co-authors

- J. Wei, H. Ao, B. Arend, S. Beher, G. Bollen, N. Bultman, F. Casagrande, W. Chang, Y. Choi, S. Cogan, C. Compton, M. Cortesi, J. Curtin, K. Davidson, X. Du, K. Elliott, B. Ewert, A. Facco[1], A. Fila, K. Fukushima, V. Ganni, A. Ganshyn, T. Ginter, T. Glasmacher, J. Guo, Y. Hao, W. Hartung, N. Hasan, M. Hausmann, K. Holland, H. C. Hseuh, M. Ikegami, D. Jager, S. Jones, N. Joseph, T. Kanemura, S. H. Kim, C. Knowles, T. Konomi, B. Kortum, E. Kwan, T. Lange, M. Larmann, T. Larter, K. Laturkar, R.E. Laxdal[2], J. LeTourneau, Z.-Y. Li, S. Lidia, G. Machicoane, C. Magsig, P. Manwiller, F. Marti, T. Maruta, E. Metzgar, S. Miller, Y. Momozaki[3], M. Mugerian, D. Morris, I. Nesterenko, C. Nguyen, P. Ostroumov, M. Patil, A. Plastun, L. Popielarski, M. Portillo, J. Priller, X. Rao, M. Reaume, K. Saito, B. M. Sherrill, M. K. Smith, J. Song, M. Steiner, A. Stolz, O. Tarasov, B. Tousignant, R. Walker, X. Wang, J. Wenstrom, G. West, K. Witgen, M. Wright, T. Xu, Y. Yamazaki, T. Zhang, Q. Zhao, S. Zhao, Michigan State University, East Lansing, MI, USA
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# References

[1] J. Wei *et al.*, "Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams", *Modern Physics Letters A,* vol. 37, pp. 2230006, 2022. Doi:10.1142/S0217732322300063

[2] T. Kanemura, M. LaVere, R. Madendorp, F. Marti, T. Maruta, Y. Momozaki, P. N. Ostroumov, A. S. Plastun, J. Wei, Q. Zhao, "Experimental demonstration of the thin-film liquid-metal jet as a charge stripper," *Phys. Rev. Lett.,* vol. 128, pp. 212301, 2022.

[3] P. N. Ostroumov, K. Fukushima, T. Maruta, A. S. Plastun, J. Wei, T. Zhang, Q. Zhao, "First simultaneous acceleration of multiple charge states of heavy ion beams in a large-scale superconducting linear accelerator," *Phys. Rev. Lett.,* vol. 126, 114801, 2021.

[4] A. Facco et al., "Superconducting resonators development for the FRIB and ReA Linacs at MSU: recent achievements and future goals," in *Proc. IPAC'12*, New Orleans, USA, pp. 61-63, 2012.

[5] T. Xu *et al.*, "Completion of FRIB superconducting linac and phased beam commissioning", in *Proc. SRF'21*, East Lansing, USA, pp. 197-202, 2021.

[6] V. Ganni, P. Knudsen, D. Arenius, and F. Casagrande, "Application of JLab 12 GeV helium refrigeration system for the FRIB accelerator at MSU," in *Advances in Cryogenic Engineering,* vol. 59A, AIP Conference Proceedings 1573, edited by J.G. Weisend II *et al*., American Institute of Physics, Melville, USA (2014) pp. 323-328.

[7] S. Kim et al., "Experience and Lessons in FRIB Superconducting Quarter-wave Resonator Commissioning," in *Proc. NAPAC'19*, Lansing, USA, pp. 646-649, 2019.

[8] P.N. Ostroumov *et al.,* "Accelerator and beam physics challenges in support of FRIB experiments", in *Proc. IPAC'23,* Venice, Italy, pp. 1109-1112, 2023.

[9] M. Hausmann, A.M. Aaron, A.M. Amthor, M. Avilov, L. Bandura, R. Bennett, G. Bollen, T. Borden, T.W. Burgess, S.S. Chouhan, V.B. Graves, W. Mittig, D.J. Morrissey, F. Pellemoine, M. Portillo, R.M. Ronningen, M. Schein, B.M. Sherrill, and A. Zeller, "Design of the Advanced Rare Isotope Separator ARIS at FRIB", *Nucl. Instrum. Methods Phys. Res.* B, vol. 317, pp. 349-353, 2013.

[10] M. Portillo, B.M. Sherrill, Y. Choi, M. Cortesi, K. Fukushima, M. Hausmann, E. Kwan, S. Lidia, P.N. Ostroumov, R. Ringle, M.K. Smith, M. Steiner, O.B. Tarasov, A.C.C. Villari, and T. Zhang, "Commissioning of the Advanced Rare Isotope Separator ARIS at FRIB", *Nucl. Instrum. Methods Phys. Res.* B, vol. 540, pp. 151-157, 2023.

[11] L. Bandura, B. Erdelyi, M. Hausmann, T. Kubo, J. Nolen, M. Portillo, and B.M. Sherrill, "Fragment separator momentum compression schemes", *Nucl. Instrum. Methods Phys. Res.* A, vol. 645, pp. 182-186, 2011.

12] O.B. Tarasov and D. Bazin, "LISE++: radioactive beam production with in-flight separators", *Nucl. Instrum. Methods Phys. Res.* B, vol. 266, p. 4657-4664, (2008).

[13] S.M. Lidia, "Diagnostics for high power accelerator machine protection systems", in *Proc. IBIC'14*, Monterey, USA, paper TUIYB1, pp. 239-249, 2014.

[14] S.-H. Kim *et al.,* "Overview of ten-year operation of the superconducting linear accelerator at the Spallation Neutron Source," *Nucl. Instrum. Methods. Phys. Res.* A, vol. 852, pp. 20–32, 2017. doi:10.1016/j.nima.2017.02.009

[15] W. Chang *et al.,* "Automation of FRIB SRF cavities and SC solenoid turn-on/off," this conference, FRIBA05.

[16] W. Hartung *et al*., "Investigation of plasma processing for coaxial resonators," this conference, THIXA01.

[17] K. Saito, "Development of transformative cavity processing: superiority of electropolishing on high gradient performance over buffered chemical polishing at low frequency (322 MHz)," this conference, MOPMB026.

[18] S. Kim, "FRIB commissioning and first operation," presented at *TTC'22*, Aomori, Japan, 2022.

[19] FRIB400 whitepaper; https://frib.msu.edu/_files/pdfs/frib400_final.pdf.

[20] P.N. Ostroumov *et al*., "Elliptical superconducting RF cavities for FRIB energy upgrade", *Nucl. Instrum. Methods Phys. Res.*, A, vol. 888 (2018) pp. 53–63.

[21] S. Kim *et al.,* "SRF R&D for FRIB linac energy upgrade with high-performance medium-beta elliptical cavity CW cryomodules," this conference, FRIBA01.

# Thank you!